Evidence for the positive-strangeness pentaquark Θ^+ in photoproduction with the SAPHIR detector at ELSA [1]

The SAPHIR Collaboration

J. Barth [a], W. Braun [a,2], J. Ernst [b], K.-H. Glander [a],
J. Hannappel [a,2], N. Jöpen [a], H. Kalinowsky [b], F. Klein [a],
E. Klempt [b], R. Lawall [a], J. Link [b,2], D. Menze [a], W. Neuerburg [a,2],
M. Ostrick [a], E. Paul [a], H. van Pee [b], I. Schulday [a], W. J. Schwille [a],
B. Wiegers [a,2], F. W. Wieland [a], J. Wißkirchen [a,2], C. Wu [a,2].

[a]*Physikalisches Institut, Bonn University, Bonn, Germany*
[b]*Helmholtz-Institut für Strahlen- und Kernphysik, Bonn University, Bonn, Germany*

Abstract

The positive–strangeness baryon resonance Θ^+ is observed in photoproduction of the $nK^+K_s^0$ final state with the SAPHIR detector at the Bonn ELectron Stretcher Accelerator ELSA. It is seen as a peak in the nK^+ invariant mass distribution with a 4.8σ confidence level. We find a mass $M_{\Theta^+} = 1540 \pm 4 \pm 2\,\text{MeV}$ and an upper limit of the width $\Gamma_{\Theta^+} < 25\,\text{MeV}$ at 90% c.l. From the absence of a signal in the pK^+ invariant mass distribution in $\gamma p \to pK^+K^-$ at the expected strength we conclude that the Θ^+ must be isoscalar.

PACS: 14.80.-j

Key words: Other particles, pentaquark with strangeness $S = 1$.

1 Introduction

The quark model has been extremely successful in accounting for the observed meson and baryon states and their quantum numbers. Ground–state baryons are grouped into an octet **8** and a decuplet **10** with total angular momentum $J^P = 1/2^+$ and $3/2^+$, respectively. The successful prediction of the Ω^- and of its mass [1] and its subsequent experimental discovery [2] was a cornerstone in establishing SU(3) symmetry. The pattern of excited baryons was understood in terms of three quarks obeying the Pauli principle (see, e.g. [3] and refs. therein). The discovery of the J/ψ [4,5] and Υ [6] families gave final support to the quark model. The development of QCD as renormalizable field theory [7,8] and the observation of the partonic structure of nucleons in deep inelastic scattering [9] seemed to pave the way for an eventual understanding of the structure of hadronic matter.

A completely different approach to understand the nucleon was proposed by Skyrme[10,11]. He suggested that the low-energy behaviour of nucleons can be viewed as spherically symmetric soliton solution of the pion field. In this view, the baryonic nature of the nucleon is not due to quarks carrying baryon quantum number $B = 1/3$. Instead, the baryon number is interpreted as topological quantum number of the pion field [12].

A fascinating consequence of this view is the prediction of an anti–decuplet $\overline{\mathbf{10}}$. It contains a state with exotic quantum numbers, with strangeness $S = +1$ and $J^P = 1/2^+$ [13]. Walliser estimated the mass of this exotic state to be at about $1700\,\text{MeV}$ [14]. Diakonov *et al.* assigned the $N(1710)\,P_{11}$ to the non-strange member of the anti–decuplet thus fixing the mass of the exotic Θ^+ to $1530\,\text{MeV}$ [15], a value consistent with the prediction of Weigel one year later [16]. Due to its intrinsic strangeness and low mass, the only allowed strong–interaction decay modes of the Θ^+ are nK^+ and pK^0. Its width is predicted to be narrow. In quark models, the Θ^+ has a minimal quark content $uudd\bar{s}$ and is called pentaquark. In the soliton model, it is the lowest–mass state beyond the conventional octet and decuplet baryons. A recent survey can be found in [17].

These predictions stimulated an active search for the Θ^+. At SPring-8(LEPS), a 4.6σ nK^+ peak was reported in the reaction $\gamma^{12}C \rightarrow K^+K^-X$ [19]. Cuts were applied to select quasi–free processes on the neutron. After correction for the Fermi momentum, the mass was determined to $(1540 \pm 10)\,\text{MeV}$. The observed width was compatible with the instrumental resolution. An upper limit of $\Gamma < 25\,\text{MeV}$ was derived. The DIANA collaboration at ITEP [20] reported a $K_s^0 p$ enhancement produced in low-energy $K^+ Xe$ collisions, with $M = (1539 \pm 2), \Gamma < 9\,\text{MeV}$ and a statistical significance of 4.4σ.

At Jlab, a significant Θ^+ peak was observed with the CLAS detector in the exclusive reaction $d(\gamma, K^+K^-p)n$. The Θ^+ is photoproduced off the neutron and subsequently decays into nK^+. Only in case of K^-p rescattering, the proton received sufficient momentum to be detected; the neutron was identified by the missing mass [21]. The peak in the nK^+ mass distribution had a statistical significance of $5.3 \pm 0.5\sigma$; it was found at a mass of $(1542 \pm 5)\,\mathrm{MeV}$, its width was compatible with the resolution (FWHM $= 21\,\mathrm{MeV}$). The authors did not see a peak in the pK^+ mass distribution. Since the CLAS acceptance for pK^+ is not the same as that for nK^+, they cautiously suggested the Θ^+ should have isospin zero. A preliminary study of the $n\pi^+K^-K^+$ final state produced by photoproduction off protons by the CLAS collaboration [22] suggests a 4.3σ peak in the nK^+ invariant mass distribution recoiling (in the centre–of–mass system) against a K^*.

In this letter we present evidence for the Θ^+ in photoproduction of the $nK^+K_s^0$ final state off protons. A diagram which may contribute is shown in Fig. 1.
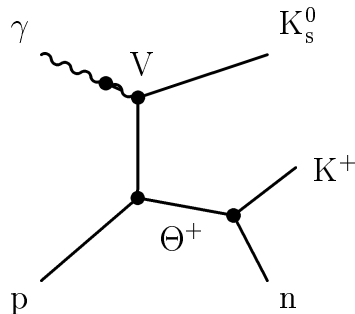

Fig. 1. *Diagram through which the Θ^+ could be produced. The V represents a vector meson.*

2 Experimental method

The reaction

$$\gamma p \to n K_s^0 K^+ \quad \text{with the decay} \quad K_s^0 \to \pi^+\pi^- \tag{1}$$

was measured with the SAPHIR detector [23] at ELSA. SAPHIR is a magnetic spectrometer covering a solid angle of approximately $0.6 \times 4\pi$ and the full polar range $0 < \vartheta < \pi$. The ELSA electron beam produced photons via bremsstrahlung in a copper foil radiator. The energies of the scattered electrons were determined in the tagging system for photon energies from $31\,\%$ to $94\,\%$ of the incident electron energy which was 2.8 GeV for the data presented in this letter. The photon beam passed through a liquid hydrogen target (3 cm

in diameter and 8 cm in length). Non–interacting photons were detected in a photon counter. The coincidences of tagger and photon counter determined the photon flux.

The target was located in the centre of a central drift chamber with 14 cylindrical layers. Charged particles leaving the target were bent in the field of a C-shaped magnet allowing for a measurement of momentum and sign of charge. The momentum resolution $\Delta p/p$ for 300 MeV/c particles in the central drift chamber was approximately 2.5 %. In forward direction a planar drift chamber improved the momentum resolution to about 1 %. The central drift chamber was surrounded by a scintillator wall to measure the time of flight (ToF). The minimum momentum to detect tracks of charged pions and protons was 50 and 150 MeV/c, respectively, with a track detection threshold depending on the position of the production vertex in the target. The data presented here were taken in 1997 and 1998 with a trigger requiring at least two charged particles. About $1.33 \cdot 10^8$ events were recorded. The data were used to determine cross sections for photoproduction of strange mesons and baryons [24],[25],[26], and of ω [27], η' [28], and Φ [29] mesons.

3   Evidence for the Θ^+

We observe the Θ^+ in the reaction

$$\gamma \mathrm{p} \rightarrow \Theta^+ \mathrm{K}_\mathrm{s}^0; \qquad \Theta^+ \rightarrow \mathrm{n} \mathrm{K}^+; \qquad \mathrm{K}_\mathrm{s}^0 \rightarrow \pi^+ \pi^- \qquad (2)$$

The neutron is identified in a kinematical fit using one constraint; the neutron momentum is reconstructed from energy and momentum conservation. Fig. 2a shows the $\mathrm{n}\mathrm{K}^+$ invariant mass distribution after cuts explained below. A clear signal is observed at $\sim 1540\,\mathrm{MeV}$ above a smooth background. The fit ascribes 63 ± 13 events (4.8σ) to the peak. By counting the four bins around the Θ^+ centre we get 55 events above background and 56 below, corresponding to a statistical significance of 5.2σ.

To determine mass and width we simulated reaction (2) by Monte Carlo, generating a narrow Θ^+. The resulting $\mathrm{n}\mathrm{K}^+$ mass distribution (after event reconstruction) is used as resolution (FWHM = 23 MeV) function which is folded with a Breit–Wigner distribution to fit the data. We find

$$\mathrm{M}_{\Theta^+} = 1540 \pm 4 \pm 2\,\mathrm{MeV} \qquad \Gamma_{\Theta^+} < 25\,\mathrm{MeV} \text{ at } 90\% \text{ c.l.} \qquad (3)$$

The errors quoted are the statistical and systematic uncertainties. The statistical error includes variation of the results when fit range or background function are changed. The systematic error is estimated from the comparison of SAPHIR and PDG masses for known stable particles.
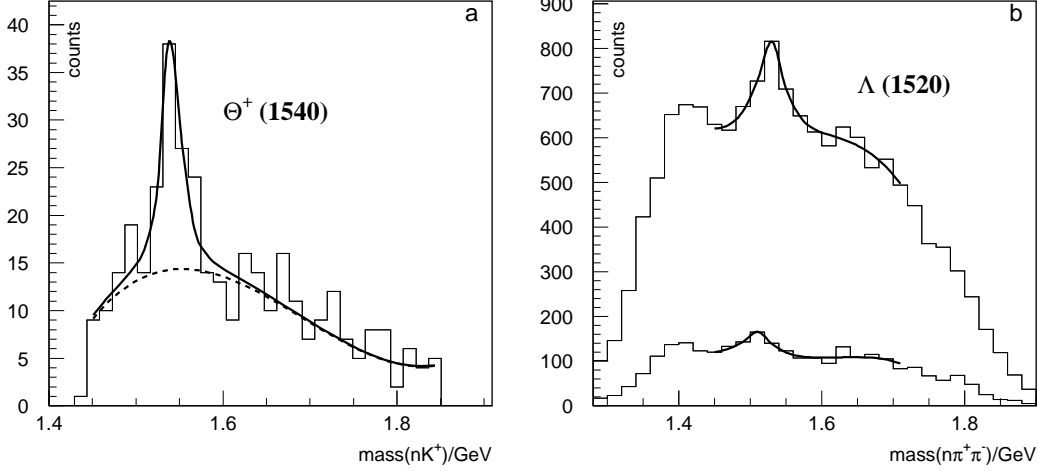
Fig. 2. *a) The* nK^+ *mass distribution after cuts in the* $\pi^+\pi^-$ *mass distribution and in the* K_s^0 *production angle. b) The* $n\pi^+\pi^-$ *invariant mass distribution showing the* $\Lambda(1520)$ *without (upper curve) and with (lower curve)* $\cos\vartheta_{\pi^+\pi^-}$ *cut. The solid lines represent fits using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background.*

A series of cuts has been applied to arrive at Fig. 2a. Events are subjected to kinematical fits to the hypotheses $\gamma p \rightarrow n\pi^+\pi^-K^+$ and $\gamma p \rightarrow n\pi^+\pi^-\pi^+$. The confidence level for the former hypothesis is required to exceed 1%, while the latter hypothesis should have a probability of less than 1%. To further clean the data, we rejected events which passed one of the following hypotheses (*): $\gamma p \rightarrow p\pi^+\pi^-$, $\gamma p \rightarrow pK^+K^-$, $\gamma p \rightarrow pe^+e^-$, $\gamma p \rightarrow p\pi^+\pi^-\pi^0$, $\gamma p \rightarrow p\pi^-K^+$, $\gamma p \rightarrow p\pi^-\pi^0K^+$.

We require identification of two pions and of one K^+ by time–of–flight. A cut in the $\pi^+\pi^-$ invariant mass from 480 to 518 MeV has been applied which enhances the fraction of $nK^+K_s^0$ events. We observe that the K_s^0 from Θ^+ production is preferentially produced in forward direction. A $\cos\vartheta_{K_s^0} > 0.5$ cut reduces the signal strength by a factor of 2 only while the background is reduced to 1/5. $\vartheta_{K_s^0}$ denotes the center–of–mass angle between the K_s^0 and the photon beam direction. In the $n\pi^+\pi^-$ mass distribution (Fig. 2b), the $\Lambda(1520)$ is clearly seen with 530 ± 90 events. The $\cos\vartheta_{\pi^+\pi^-} > 0.5$ cut considerably reduces the $\Lambda(1520)$ signal.

The size of the nK^+ peak in Fig. 2a does not depend on the kinematical fits and is not generated by them. The signal can also be seen without the kinematical anti–cuts (*) and without the cut in $\cos\vartheta_{K_s^0}$, yet above a larger background. All kinematical fits reduce the background but do not lead to noticeable losses in the signal strength; the $\cos\vartheta_{K_s^0}$ cut reduces the signal by about a factor 2.

Fig. 3a presents the $\pi^+\pi^-$ mass distribution after applying a mass cut in the nK^+ invariant mass from 1.515 to 1.559 MeV. A clear K_s^0 signal is ob-
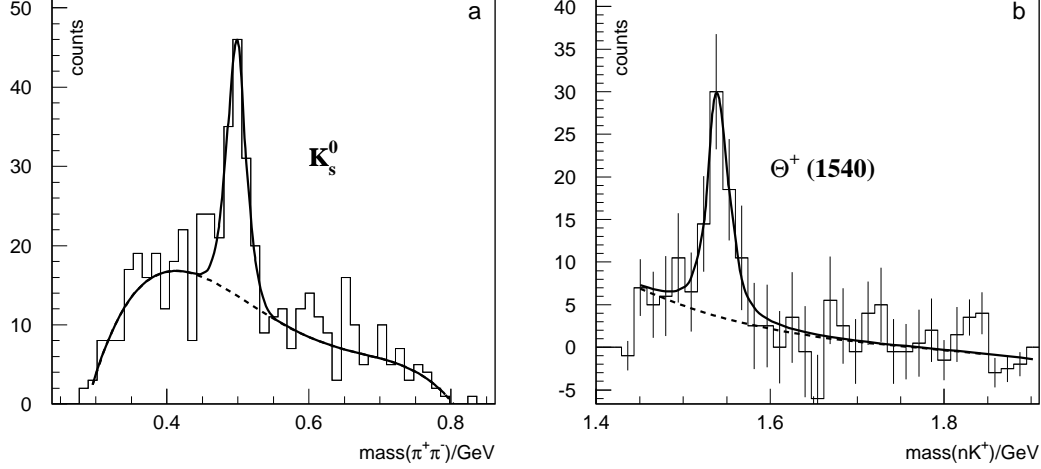
Fig. 3. *a) The $\pi^+\pi^-$ mass distribution after a cut in the nK^+ mass distribution selecting Θ^+ events with a fit using a resolution function and a polynomial background. b) The nK^+ mass distribution after side-bin subtraction of the background under the K_s^0. The residual background is the reflection from the $\Lambda(1520)$ surviving the $\cos\vartheta_{K_s^0}$ cut. The solid line represents a fit using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background.*

served. We now verify that the peaks in Fig. 2a and 3a are correlated. Fig. 3b shows the side–bin subtracted nK^+ mass distribution. The K_s^0 is defined by the 480 to 516 MeV mass interval, the two side bins, counted with half weight, extend from 417 to 453 and from 543 to 579 MeV, respectively. In the subtracted spectrum (Fig. 3b) the Θ^+ is seen above a rather small background. The background resembles the distribution expected from the reflection of the $\Lambda(1520)K^+$; its content agrees with the number of $\Lambda(1520)$ events in the lower curve of Fig. 2b. We conclude that the $nK^+K_s^0$ final state is reached dominantly via the intermediate states $\Theta^+K_s^0$ or $\Lambda(1520)K^+$. Note that fig. 3b was not used to determine the signal strength.

From the number of Θ^+ events observed in the full angular range, the mean cross section for Θ^+ production in the photon energy range from threshold (1.74 GeV) to 2.6 GeV is estimated to about 200 nb, apparently rising with energy. It may be compared to those for other reactions with strange particles in the final state like $\gamma p \to K^+\Lambda$, $\gamma p \to K^+\Sigma$, and $\gamma p \to K^+\Lambda(1520)$ which are of the order of $800 - 1200$ nb at $E_\gamma = 2$ GeV.

4   The isospin of the Θ^+

If the Θ^+ is a member of the anti–decuplet, it has quantum numbers $\Theta^+(1540)P_{01}$. In particular it is predicted to be an isoscalar. A conventional explanation would interpret the Θ^+ as NK bound state. Isospins 0 and 1 are both possi-

ble; isospin 1 would lead to three charge states $\Theta^0, \Theta^+, \Theta^{++}$. Capstick, Page and Roberts [18] point out that the Θ^+ could be a member of an isospin quintet with charges from -1 to +3 where the $Q = +3$ state has a (uuuū$\bar{s}$) quark–model configuration. An isotensor resonance could be produced with an isospin conserving amplitude as depicted in Fig. 4 (left). Decays of an isotensor Θ^+ into pK^0 and pK$^+$ are isospin violating; hence an isotensor Θ^+ is expected to be narrow [18].

The photoproduction of the pK$^+$K$^-$ final state has been studied recently by us [29], with the focus on Φ production. We use these data to search for the doubly charged Θ^{++} in the reaction chain

$$\gamma p \rightarrow \Theta^{++} K^-; \qquad \Theta^{++} \rightarrow pK^+. \tag{4}$$

In analogy to the K$_s^0$ above, we have applied a cut $\cos\vartheta_{K^-} > 0.5$ to select forward K$^-$. Fig. 4 (right) shows the resulting pK$^+$ invariant mass spectrum. The data are consistent with a small structure at 1540 MeV. The fit assigns 75 ± 35 events to it.
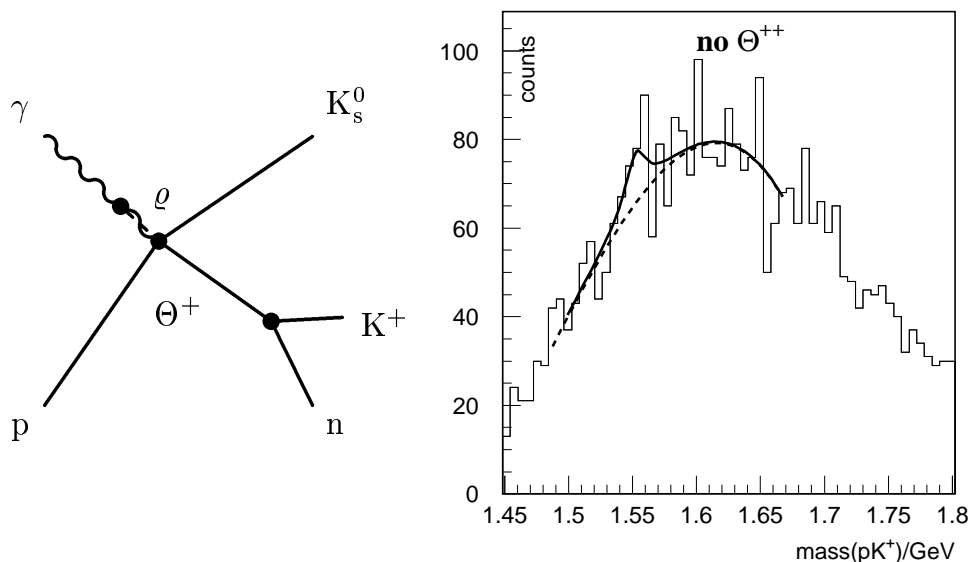

Fig. 4. *Left: Diagram allowing for production of an isotensor resonance. Right: The* pK$^+$ *invariant mass distribution in the* pK$^+$K$^-$ *final state. The solid line represents a fit using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background. If the* Θ^+ *would be an isovector or isotensor state, it would yield a much larger peak containing more than 5000 events.*

The number of Θ^{++} events we expect depends on the isospin: Clebsch–Gordan coefficients favour Θ^{++} over Θ^+ by a factor 3 (for I=2) or 4 (for I=1) while the Θ^{++} does not exist in case of I=0. Experimentally, the final state K$^+$K$^-$ offers an additional factor 3 since 1/2 of all K^0 are produced as K$_L^0$ and escape undetected, and the K$_s^0$ is observed only with a fraction $\sim 2/3$. In case the Θ^+ is an isovector or isotensor we should observe 9 or 12 times more Θ^{++} events,

respectively. Also, the SAPHIR acceptance is considerably larger for the fully constrained pK^+K^- events. We thus expect a peak with more than 5000 Θ^{++} in Fig. 4 (right), far above the observed level. We conclude that the Θ^+ is isoscalar.

5 Summary and conclusions

We have studied photoproduction of the $nK^+K_s^0$ final state. In the nK^+ invariant mass distribution we observe a 4.8σ peak at a mass of $M_{\Theta^+} = 1540 \pm 4 \pm 2\,\text{MeV}$. The peak is strikingly narrow: we quote an upper limit (at 90% c.l.) of $\Gamma_{\Theta^+} < 25\,\text{MeV}$. Mass and width are compatible with results obtained elsewhere. Here, the Θ^+ is observed for the first time in the reaction $\gamma p \to nK^+K_s^0$. The cross section for $\gamma p \to \Theta^+ \overline{K}^0$ in the photon energy range from 1.7 to 2.6 GeV is of similar size as the cross section for ϕ photoproduction and smaller by a factor 4 than for other final states with open strangeness like $\gamma p \to \Lambda K^+$, $\gamma p \to \Sigma K^+$, or $\gamma p \to \Lambda(1520)K^+$.

The Θ^+ has strangeness $S = +1$ and cannot be a three-quark baryon. In the quark picture, it is a pentaquark $(uudd\bar{s})$. In the related reaction $\gamma p \to pK^+K^-$, we have searched for a doubly charged isospin partner of the Θ^+. From the absence of a signal at the expected strength we deduce that the Θ^+ is an isoscalar.

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